Princeton University

Computer Science 217: Introduction to Programming Systems

Program and Programming Style

The material for this lecture is drawn, in part, from *The Practice of Programming* (Kernighan & Pike) Chapter 1

For Your Amusement

"Any fool can write code that a computer can understand. Good programmers write code that humans can understand." -- Martin Fowler

"Good code is its own best documentation. As you're about to add a comment, ask yourself, 'How can I improve the code so that this comment isn't needed?'" -- Steve McConnell

"Programs must be written for people to read, and only incidentally for machines to execute." -- Abelson / Sussman

"Everything should be built top-down, except the first time." -- Alan Perlis

"Programming in the Large" Steps

Design & Implement
- Program & programming style <-- we are here
- Common data structures and algorithms
- Modularity
- Building techniques & tools (done)

Debug
- Debugging techniques & tools

Test
- Testing techniques (done)

Maintain
- Performance improvement techniques & tools

Goals of this Lecture

Help you learn about:
- Good **program** style
- Good **programming** style

Why?
- A well-styled program is more likely to **be correct** than a poorly-styled program
- A well-styled program is more likely to **stay correct** (i.e. is more maintainable) than a poorly-styled program
- A power programmer knows the qualities of a well-styled program, and how to compose one quickly

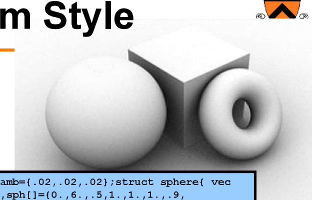
Agenda

Program style
- **Qualities of a good program**

Programming style
- How to write a good program quickly

Motivation for Program Style

Who reads your code?
- The compiler
- Other programmers



```
typedef struct{double x,y,z}vec;vec U,black,amb={.02,.02,.02};struct sphere{ vec
cen,color;double rad,kd,ks,kt,kl,ir}*s,*best,sph[]={0.,6.,.5,1.,1.,1.,.9,
.05,.2,.85,0.,1.7,-1.,8.,-.5,1.,.5,.2,1.,.7,.3,0.,.05,1.2,1.,8.,-.5,.1,.8,.8,
1.,.3,.7,0.,0.,1.2,3.,-6.,15.,1.,.8,1.,7.,0.,0.,0.,.6,1.5,-3.,-3.,12.,.8,1.,
1.,5.,0.,0.,0.,.5,1.5,};yx;double u,b,tmin,sqrt(),tan();double vdot(A,B)vec A
,B;{return A.x*B.x+A.y*B.y+A.z*B.z;}vec vcomb(a,A,B)double a;vec A,B;{B.x+=a*
A.x;B.y+=a*A.y;B.z+=a*A.z;return B;}vec vunit(A)vec A;{return vcomb(1./sqrt(
vdot(A,A)),A,black);}struct sphere*intersect(P,D)vec P,D;{best=0;tmin=1e30;s=
sph+5;while(s--sph)b=vdot(D,U=vcomb(-1.,P,s-cen)),u=b*b-vdot(U,U)+s-rad*s -
rad,u=u0?sqrt(u):1e31,u=b-u1e-7?b-u:b+u,tmin=u=1e-7&&u<tmin?best=s,u: tmin;return
best;}vec trace(level,P,D)vec P,D;{double d,eta,e;vec N,color; struct
sphere*s,*l;if(!level--)return black;if(s=intersect(P,D));else return
amb;color=amb;eta=s-ir;d= -vdot(D,N=vunit(vcomb(-1.,P=vcomb(tmin,D,P),s-cen
)));if(d<0)N=vcomb(-1.,N,black),eta=1/eta,d= -d;l=sph+5;while(l--sph)if((e=l -
kl*vdot(N,U=vunit(vcomb(-1.,P,l-cen))))0&&intersect(P,U)==l)color=vcomb(e ,l-
color,color);U=s-color;color.x*=U.x;color.y*=U.y;color.z*=U.z;e=1-eta* eta*(1-
d*d);return vcomb(s-kt,e0?trace(level,P,vcomb(eta,D,vcomb(eta*d-sqrt
(e),N,black))):black,vcomb(s-ks,trace(level,P,vcomb(2*d,N,D)),vcomb(s-kd,
color,vcomb(s-kl,U,black))));}main(){printf("%d %d\n",32,32);while(yx<32*32)
U.x=yx%32-32/2,U.z=32/2-yx++/32,U.y=32/2/tan(25/114.5915590261),U=vcomb(255.,
trace(3,black,vunit(U)),black),printf("%.0f %.0f %.0f\n",U);}
```

This is a working ray tracer! (courtesy of Paul Heckbert)

Motivation for Program Style

Why does program style matter?

- Correctness
  - The clearer a program is, the more likely it is to be correct
- Maintainability
  - The clearer a program is, the more likely it is to **stay** correct over time

Good program ≈ clear program

Choosing Names

Use descriptive names for globals and functions

- E.g., `display`, `CONTROL`, `CAPACITY`

Use concise names for local variables

- E.g., `i` (not `arrayIndex`) for loop variable

Use case judiciously

- E.g., Stack_push (Module_function)
  CAPACITY (constant)
  buf (local variable)

Use a consistent style for compound names

- E.g., `frontsize`, `frontSize`, `front_size`

Use active names for functions that do something

- E.g., `getchar()`, `putchar()`, `Check_octal()`, etc.

Not necessarily for functions that are something: sin(), sqrt()

Using C Idioms

Use C idioms

- Example: Set each array element to 1.0.
- Bad code (complex for no obvious gain)

```
i = 0;
while (i <= n-1)
   array[i++] = 1.0;
```

- Good code (not because it's vastly simpler—it isn't!—but because it uses a standard idiom that programmers can grasp at a glance)

```
for (i=0; i<n; i++)
   array[i] = 1.0;
```

- Don't feel obliged to use C idioms that decrease clarity

Revealing Structure: Expressions

Use natural form of expressions

- Example: Check if integer `n` satisfies `j < n < k`
- Bad code

```
if (!(n >= k) && !(n <= j))
```

- Good code

```
if ((j < n) && (n < k))
```

- Conditions should read as you'd say them aloud
  - Not "Conditions shouldn't read as you'd never say them in other than a purely internal dialog!"

Revealing Structure: Expressions

Parenthesize to resolve ambiguity

- Example: Check if integer `n` satisfies `j < n < k`
- Common code

```
if (j < n && n < k)
```

Does this code work?

- Clearer code (maybe)

```
if ((j < n) && (n < k))
```

It's clearer *depending* on whether your audience can be trusted to know the precedence of all the C operators. Use your judgment on this!

Revealing Structure: Expressions

Parenthesize to resolve ambiguity (cont.)

- Example: read and print character until end-of-file
- Bad code

```
while (c = getchar() != EOF)
   putchar(c);
```

Does this code work?

- Good-ish code

```
while ((c = getchar()) != EOF)
   putchar(c);
```

- (Code with side effects inside expressions is never truly "good", but at least this code is a standard idiomatic way to write it in C)

Revealing Structure: Expressions

Break up complex expressions

- Example: Identify chars corresponding to months of year
- Bad code

```
if ((c == 'J') || (c == 'F') || (c ==
'M') || (c == 'A') || (c == 'S') || (c
== 'O') || (c == 'N') || (c == 'D'))
```

- Good code – lining up things helps

```
if ((c == 'J') || (c == 'F') ||
    (c == 'M') || (c == 'A') ||
    (c == 'S') || (c == 'O') ||
    (c == 'N') || (c == 'D'))
```

- Very common, though, to elide parentheses

```
if (c == 'J' || c == 'F' || c == 'M' ||
    c == 'A' || c == 'S' || c == 'O' ||
    c == 'N' || c == 'D')
```


Revealing Structure

```
if (c == 'J' || c == 'F' || c == 'M' ||
    c == 'A' || c == 'S' || c == 'O' ||
    c == 'N' || c == 'D')
  do_this();
else do_that();
```

Perhaps better in this case: a switch statement

```
switch (c) {
  case 'J': case 'F': case 'M':
  case 'A': case 'S': case 'O':
  case 'N': case 'D':
    do_this();
    break;
  default:
    do_that();
}
```


Revealing Structure: Spacing

Use readable/consistent spacing

- Example: Assign each array element a[j] to the value j.
- Bad code

```
for (j=0;j<100;j++) a[j]=j;
```

- Good code

```
for (j = 0; j < 100; j++)
    a[j] = j;
```

- Often can rely on auto-indenting feature in editor

Revealing Structure: Indentation

Use readable/consistent/correct indentation

- Example: Checking for leap year (does Feb 29 exist?)

```
legal = TRUE;
if (month == FEB)
{  if ((year % 4) == 0)
      if (day > 29)
         legal = FALSE;
   else
      if (day > 28)
         legal = FALSE;
}
```

Does this code work?

```
legal = TRUE;
if (month == FEB)
{  if ((year % 4) == 0)
   {  if (day > 29)
         legal = FALSE;
   }
   else
   {  if (day > 28)
         legal = FALSE;
   }
}
```

Does this code work?

Revealing Structure: Indentation

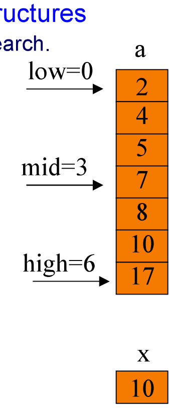
Use "else-if" for multi-way decision structures

- Example: Comparison step in a binary search.
- Bad code

```
if (x < a[mid])
  high = mid - 1;
else
  if (x > a[mid])
     low = mid + 1;
  else
     return mid;
```

- Good code

```
if (x < a[mid])
   high = mid - 1;
else if (x > a[mid])
   low = mid + 1;
else
   return mid;
```



Revealing Structure: "Paragraphs"

Use blank lines to divide the code into key parts

```
#include <stdio.h>
#include <stdlib.h>

/* Read a circle's radius from stdin, and compute and write its
   diameter and circumference to stdout.  Return 0 if successful. */

int main(void)
{  const double PI = 3.14159;
   int radius;
   int diam;
   double circum;

   printf("Enter the circle's radius:\n");
   if (scanf("%d", &radius) != 1)
   {  fprintf(stderr, "Error: Not a number\n");
      exit(EXIT_FAILURE);  /* or:  return EXIT_FAILURE; */
   }
…
```

Revealing Structure: "Paragraphs"

Use blank lines to divide the code into key parts

```
   diam = 2 * radius;
   circum = PI * (double)diam;

   printf("A circle with radius %d has diameter %d\n",
      radius, diam);
   printf("and circumference %f.\n", circum);

   return 0;
}
```


Composing Comments

Master the language and its idioms

- Let the code speak for itself
- And then…

Compose comments that add new information

```
i++;  /* Add one to i. */
```

Comment paragraphs of code, not lines of code

- E.g., "Sort array in ascending order"

Comment global data

- Global variables, structure type definitions, field definitions, etc.

Compose comments that agree with the code!!!

- And change as the code itself changes!!!

Composing Comments

Comment sections ("paragraphs") of code, not lines of code

```
#include <stdio.h>
#include <stdlib.h>

/* Read a circle's radius from stdin, and compute and write its
   diameter and circumference to stdout.  Return 0 if successful. */

int main(void)
{  const double PI = 3.14159;
   int radius;
   int diam;
   double circum;

   /* Read the circle's radius. */
   printf("Enter the circle's radius:\n");
   if (scanf("%d", &radius) != 1)
   {  fprintf(stderr, "Error: Not a number\n");
      exit(EXIT_FAILURE);  /* or:  return EXIT_FAILURE; */
   }
…
```


Composing Comments

```
   /* Compute the diameter and circumference. */
   diam = 2 * radius;
   circum = PI * (double)diam;

   /* Print the results. */
   printf("A circle with radius %d has diameter %d\n",
      radius, diam);
   printf("and circumference %f.\n", circum);

   return 0;
}
```


Composing Function Comments

Describe **what a caller needs to know** to call the function properly

- Describe **what the function does**, not **how it works**
- Code itself should clearly reveal how it works…
- If not, compose "paragraph" comments within definition

Describe **input**

- Parameters, files read, global variables used

Describe **output**

- Return value, parameters, files written, global variables affected

Refer to parameters **by name**

Composing Function Comments

Bad function comment

```
/* decomment.c */

/* Read a character.  Based upon the character and
   the current DFA state, call the appropriate
   state-handling function.  Repeat until
   end-of-file. */

int main(void)
{
   …
}
```

Describes **how the function works**

30% of the class last year lost points on assignment 1 for a "how" instead of "what" comment on main()

Composing Function Comments

Good function comment

```
/* decomment.c */

/* Read a C program from stdin.  Write it to
   stdout with each comment replaced by a single
   space.  Preserve line numbers.  Return 0 if
   successful, EXIT_FAILURE if not. */

int main(void)
{
   …
}
```

- Describes **what the function does**

Using Modularity

Abstraction is the key to managing complexity
- Abstraction is a tool (the only one???) that people use to understand complex systems
- Abstraction allows people to know *what* a (sub)system does without knowing *how*

Proper modularity is the manifestation of abstraction
- Proper modularity makes a program’s abstractions explicit
- Proper modularity can dramatically increase clarity
- ⇒ Programs should be modular

However
- *Excessive* modularity can *decrease* clarity!
- *Improper* modularity can *dramatically* decrease clarity!!!
- ⇒ Programming is an art

Modularity Examples

Examples of **function**-level modularity
- Character I/O functions such as `getchar()` and `putchar()`
- Mathematical functions such as `sin()` and `gcd()`
- Function to sort an array of integers

Examples of **file**-level modularity
- (See subsequent lectures)

Program Style Summary

Good program ≈ clear program

Qualities of a clear program
- Uses appropriate names
- Uses common idioms
- Reveals program structure
- Contains proper comments
- Is modular

Agenda

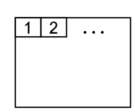
Program style
- Qualities of a good program

Programming style
- **How to write a good program quickly**

Bottom-Up Design

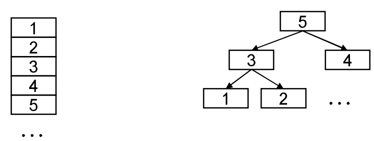
Bottom-up design ☹
- Design one part of the system in detail
- Design another part of the system in detail
- Combine
- Repeat until finished

Bottom-up design in **painting**
- Paint part of painting in complete detail
- Paint another part of painting in complete detail
- Combine
- Repeat until finished
- *Unlikely to produce a good painting*
  (except sometimes: see the movie “Tim’s Vermeer”)



Bottom-Up Design

Bottom-up design in **programming**
- Compose part of program in complete detail
- Compose another part of program in complete detail
- Combine
- Repeat until finished
- *Unlikely to produce a good program*



Top-Down Design

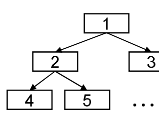
Top-down design ☺
- Design entire product with minimal detail
- Successively refine until finished

Top-down design in **painting**
- Sketch the entire painting with minimal detail
- Successively refine until finished

Top-Down Design

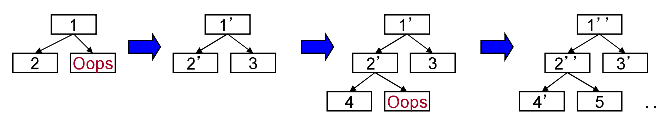
Top-down design in **programming**
- Define main() function in pseudocode with minimal detail
- Refine each pseudocode statement
  - Small job ⇒ replace with real code
  - Large job ⇒ replace with function call
- Repeat in (mostly) breadth-first order until finished

- Bonus: Product is naturally **modular**



Top-Down Design in Reality

Top-down design in programming **in reality**
- Define main() function in pseudocode
- Refine each pseudocode statement
  - Oops! Details reveal design error, so…
  - Backtrack to refine existing (pseudo)code, and proceed
- Repeat in (mostly) breadth-first order until finished



Example: Text Formatting

Functionality (derived from King Section 15.3)
- **Input**: ASCII text, with arbitrary spaces and newlines
- **Output**: the same text, left and right justified
  - Fit as many words as possible on each 50-character line
  - Add even spacing between words to right justify the text
  - No need to right justify last line
- **Assumptions**
  - "Word" is a sequence of non-white-space chars followed by a white-space char or end-of-file
  - No word is longer than 20 chars

Example Input and Output

Input

```
"C is quirky,    flawed, and an    enormous success.
   While     accidents of        history
surely helped,
it    evidently satisfied a     need for a
system implementation      language   efficient enough
 to displace assembly language,
yet sufficiently abstract  and fluent to        describe
algorithms     and interactions in a
wide variety of environments." -- Dennis Ritchie
```

Output

```
"C is quirky, flawed,  and  an  enormous  success.
While  accidents  of  history  surely  helped,  it
evidently  satisfied  a  need  for  a  system
implementation  language  efficient  enough  to
displace  assembly  language,  yet  sufficiently
abstract and fluent  to  describe  algorithms  and
interactions in a wide variety  of  environments."
-- Dennis Ritchie
```

Caveats

Caveats concerning the following presentation

- Function comments and some blank lines are omitted
  - Because of space constraints
  - Don't do that!!!
- Design sequence is idealized
  - In reality, typically much backtracking would occur

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The main() Function

```
int main(void)
{  <clear line>
   <read a word>
   while (<there is a word>)
   {  if (<word doesn't fit on line>)
      {  <write justified line>
         <clear line>
      }
      <add word to line>
      <read a word>
   }
   if (<line isn't empty>)
      <write line>
   return 0;
}
```

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The main() Function

```
enum {MAX_WORD_LEN = 20};
int main(void)
{  char word[MAX_WORD_LEN+1];
   int wordLen;
   <clear line>
   wordLen = readWord(word);
   while (<there is a word>)
   {  if (<word doesn't fit on line>)
      {  <write justified line>
         <clear line>
      }
      <add word to line>
      wordLen = readWord(word);
   }
   if (<line isn't empty>)
      <write line>
   return 0;
}
```

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The main() Function

```
enum {MAX_WORD_LEN = 20};
int main(void)
{  char word[MAX_WORD_LEN+1];
   int wordLen;
   <clear line>
   wordLen = readWord(word);
   while (wordLen != 0)
   {  if (<word doesn't fit on line>)
      {  <write justified line>
         <clear line>
      }
      <add word to line>
      wordLen = readWord(word);
   }
   if (<line isn't empty>)
      <write line>
   return 0;
}
```

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The main() Function

```
enum {MAX_WORD_LEN = 20};
int main(void)
{  char word[MAX_WORD_LEN+1];
   int wordLen;
   int lineLen;
   <clear line>
   wordLen = readWord(word);
   while (wordLen != 0)
   {  if (<word doesn't fit on line>)
      {  <write justified line>
         <clear line>
      }
      <add word to line>
      wordLen = readWord(word);
   }
   if (lineLen > 0)
      <write line>
   return 0;
}
```

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The main() Function

```
enum {MAX_WORD_LEN = 20};
enum {MAX_LINE_LEN = 50};
int main(void)
{  char word[MAX_WORD_LEN+1];
   char line[MAX_LINE_LEN+1];
   int wordLen;
   int lineLen;
   <clear line>
   wordLen = readWord(word);
   while (wordLen != 0)
   {  if (<word doesn't fit on line>)
      {  <write justified line>
         <clear line>
      }
      lineLen = addWord(word, line, lineLen);
      wordLen = readWord(word);
   }
   if (lineLen > 0)
      <write line>
   return 0;
}
```

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The main() Function

```
enum {MAX_WORD_LEN = 20};
enum {MAX_LINE_LEN = 50};
int main(void)
{  char word[MAX_WORD_LEN+1];
   char line[MAX_LINE_LEN+1];
   int wordLen;
   int lineLen;
   <clear line>
   wordLen = readWord(word);
   while (wordLen != 0)
   {  if (<word doesn't fit on line>)
      {  <write justified line>
         <clear line>
      }
      lineLen = addWord(word, line, lineLen);
      wordLen = readWord(word);
   }
   if (lineLen > 0)
      puts(line);
   return 0;
}
```


The main() Function

```
enum {MAX_WORD_LEN = 20};
enum {MAX_LINE_LEN = 50};
int main(void)
{  char word[MAX_WORD_LEN+1];
   char line[MAX_LINE_LEN+1];
   int wordLen;
   int lineLen = 0;
   int wordCount = 0;
   <clear line>
   wordLen = readWord(word);
   while (wordLen != 0)
   {  if (<word doesn't fit on line>)
      {  writeLine(line, lineLen, wordCount);
         <clear line>
      }
      lineLen = addWord(word, line, lineLen);
      wordLen = readWord(word);
   }
   if (lineLen > 0)
      puts(line);
   return 0;
}
```

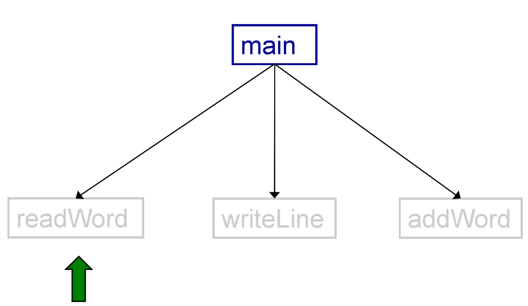

The main() Function

```
enum {MAX_WORD_LEN = 20};
enum {MAX_LINE_LEN = 50};
int main(void)
{  char word[MAX_WORD_LEN+1];
   char line[MAX_LINE_LEN+1];
   int wordLen;
   int lineLen = 0;
   int wordCount = 0'
   <clear line>
   wordLen = readWord(word);
   while (wordLen != 0)
   {  if ((wordLen + 1 + lineLen) > MAX_LINE_LEN)
      {  writeLine(line, lineLen, wordCount);
         <clear line>
      }
      lineLen = addWord(word, line, lineLen);
      wordLen = readWord(word);
   }
   if (lineLen > 0)
      puts(line);
   return 0;
}
```


The main() Function

```
enum {MAX_WORD_LEN = 20};
enum {MAX_LINE_LEN = 50};
int main(void)
{  char word[MAX_WORD_LEN+1];
   char line[MAX_LINE_LEN+1];
   int wordLen;
   int lineLen = 0;
   int wordCount = 0;
   line[0] = '\0'; lineLen = 0; wordCount = 0;
   wordLen = readWord(word);
   while (wordLen != 0)
   {  if ((wordLen + 1 + lineLen) > MAX_LINE_LEN)
      {  writeLine(line, lineLen, wordCount);
         line[0] = '\0'; lineLen = 0; wordCount = 0;
      }
      lineLen = addWord(word, line, lineLen);
      wordLen = readWord(word);
   }
   if (lineLen > 0)
      puts(line);
   return 0;
}
```


Status



The readWord() Function

```
int readWord(char *word)
{
   <skip over white space>

   <read chars, storing up to MAX_WORD_LEN in word>

   <return length of word>
}
```

The readWord() Function

```
int readWord(char *word)
{
   int ch;

   /* Skip over white space. */
   ch = getchar();
   while ((ch != EOF) && isspace(ch))
      ch = getchar();

   <read up to MAX_WORD_LEN chars into word>

   <return length of word>
}
```

Note the use of a function from the standard library. Very appropriate for your top-down design to target things that are already built.

The readWord() Function

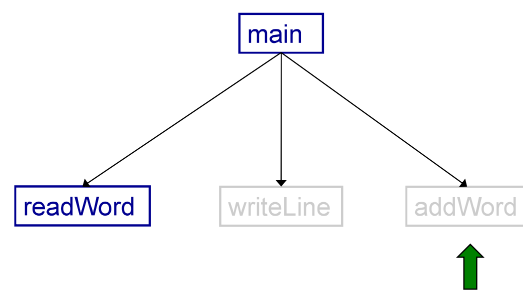
```
int readWord(char *word)
{
   int ch;
   int pos = 0;

   /* Skip over white space. */
   ch = getchar();
   while ((ch != EOF) && isspace(ch))
      ch = getchar();

   /* Read up to MAX_WORD_LEN chars into word. */
   while ((ch != EOF) && (! isspace(ch)))
   {  if (pos < MAX_WORD_LEN)
      {  word[pos] = (char)ch;
         pos++;
      }
      ch = getchar();
   }
   word[pos] = '\0';

   <return length of word>
}
```


The readWord() Function

```
int readWord(char *word)
{
   int ch;
   int pos = 0;
   ch = getchar();

   /* Skip over white space. */
   while ((ch != EOF) && isspace(ch))
      ch = getchar();

   /* Read up to MAX_WORD_LEN chars into word. */
   while ((ch != EOF) && (! isspace(ch)))
   {  if (pos < MAX_WORD_LEN)
      {  word[pos] = (char)ch;
         pos++;
      }
      ch = getchar();
   }
   word[pos] = '\0';

   return pos;
}
```

readWord() gets away with murder here, consuming/discarding one character past the end of the word.

Status



The addWord() Function

```
int addWord(const char *word, char *line, int lineLen)
{
   <if line already contains words, then append a space>

   <append word to line>

   <return the new line length>
}
```


The addWord() Function

```
int addWord(const char *word, char *line, int lineLen)
{
   int newLineLen = lineLen;

   /* if line already contains words, then append a space. */
   if (newLineLen > 0)
   {  strcat(line, " ");
      newLineLen++;
   }

   <append word to line>

   <return the new line length>
}
```

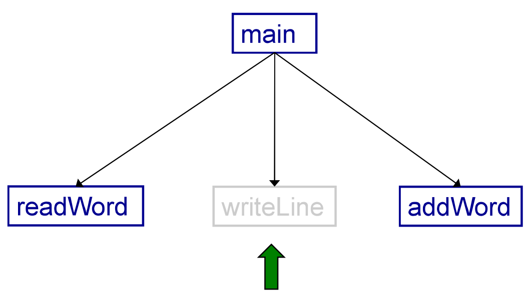
The addWord() Function

```
int addWord(const char *word, char *line, int lineLen)
{
   int newLineLen = lineLen;

   /* if line already contains words, then append a space. */
   if (newLineLen > 0)
   {  strcat(line, " ");
      newLineLen++;
   }

   strcat(line, word);

   <return the new line length>
}
```


The addWord() Function

```
int addWord(const char *word, char *line, int lineLen)
{
   int newLineLen = lineLen;

   /* If line already contains some words, then append a space. */
   if (newLineLen > 0)
   {  strcat(line, " ");
      newLineLen++;
   }

   strcat(line, word);

   newLineLen += strlen(word);
   return newLineLen;
}
```


Status



The writeLine() Function

```
void writeLine(const char *line, int lineLen, int wordCount)
{  int i;

   <compute number of excess spaces for line>

   for (i = 0; i < lineLen; i++)
   {  if (line[i] != ' ')
         putchar(line[i])
      else
      {
         <compute additional spaces to insert>

         <print a space, plus additional spaces>

         <decrease extra spaces and word count>
      }
   }
   putchar('\n');
}
```


The writeLine() Function

```
void writeLine(const char *line, int lineLen, int wordCount)
{  int i, extraSpaces;

   /* Compute number of excess spaces for line. */
   extraSpaces = MAX_LINE_LEN - lineLen;

   for (i = 0; i < lineLen; i++)
   {  if (line[i] != ' ')
         putchar(line[i])
      else
      {
         <compute additional spaces to insert>

         <print a space, plus additional spaces>

         <decrease extra spaces and word count>
      }
   }
   putchar('\n');
}
```


The writeLine() Function

```
void writeLine(const char *line, int lineLen, int wordCount)
{  int i, extraSpaces, spacesToInsert;

   /* Compute number of excess spaces for line. */
   extraSpaces = MAX_LINE_LEN - lineLen;

   for (i = 0; i < lineLen; i++)
   {  if (line[i] != ' ')
         putchar(line[i])
      else
      {  /* Compute additional spaces to insert. */
         spacesToInsert = extraSpaces / (wordCount - 1);

         <print a space, plus additional spaces>

         <decrease extra spaces and word count>
      }
   }
   putchar('\n');
}
```

The number of gaps

The writeLine() Function

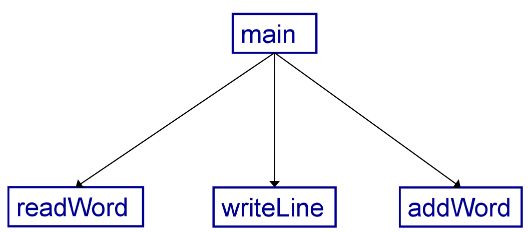
```
void writeLine(const char *line, int lineLen, int wordCount)
{  int i, extraSpaces, spacesToInsert, j;

   /* Compute number of excess spaces for line. */
   extraSpaces = MAX_LINE_LEN - lineLen;

   for (i = 0; i < lineLen; i++)
   {  if (line[i] != ' ')
         putchar(line[i])
      else
      {  /* Compute additional spaces to insert. */
         spacesToInsert = extraSpaces / (wordCount - 1);

         /* Print a space, plus additional spaces. */
         for (j = 1; j <= spacesToInsert + 1; j++)
            putchar(' ');

         <decrease extra spaces and word count>
      }
   }
   putchar('\n');
}
```

Example:
If extraSpaces is 10 and wordCount is 5, then gaps will contain 2, 2, 3, and 3 extra spaces respectively

The writeLine() Function

```
void writeLine(const char *line, int lineLen, int wordCount)
{  int i, extraSpaces, spacesToInsert, j;

   /* Compute number of excess spaces for line. */
   extraSpaces = MAX_LINE_LEN - lineLen;

   for (i = 0; i < lineLen; i++)
   {  if (line[i] != ' ')
         putchar(line[i])
      else
      {  /* Compute additional spaces to insert. */
         spacesToInsert = extraSpaces / (wordCount - 1);

         /* Print a space, plus additional spaces. */
         for (j = 1; j <= spacesToInsert + 1; j++)
            putchar(' ');

         /* Decrease extra spaces and word count. */
         extraSpaces -= spacesToInsert;
         wordCount--;
      }
   }
   putchar('\n');
}
```


Status



Complete!

Top-Down Design and Modularity

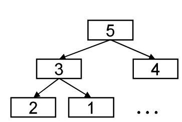
Note: Top-down design naturally yields modular code

Much more on modularity in upcoming lectures

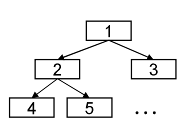
Aside: Least-Risk Design

Design process should minimize risk

Bottom-up design
- Compose each child module before its parent
- **Risk level**: high
  - May compose modules that are never used

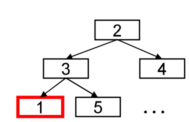


Top-down design
- Compose each parent module before its children
- **Risk level**: low
  - Compose only those modules that are required



Aside: Least-Risk Design

Least-risk design
- The module to be composed next is the one that has the **most** risk
- The module to be composed next is the one that, if problematic, will require redesign of the greatest number of modules
- The module to be composed next is the one that poses the **least** risk of needing to redesign other modules
- The module to be composed next is the one that poses the **least** risk to the system as a whole
- **Risk level**: minimal (by definition)



Aside: Least-Risk Design

Recommendation
- Work mostly top-down
- But give high priority to risky modules
- Create scaffolds and stubs as required

Summary

Program style
- Choose appropriate names (for variables, functions, …)
- Use common idioms (but not at the expense of clarity)
- Reveal program structure (spacing, indentation, parentheses, …)
- Compose proper comments (especially for functions)
- Use modularity (because modularity reveals abstractions)

Programming style
- Use top-down design and successive refinement
- But know that backtracking inevitably will occur
- And give high priority to risky modules

Are we there yet?

Now that the top-down design is done, and the program "works," does that mean we're done?

No. There are almost always things to improve, perhaps by a bottom-up pass that better uses existing libraries.

The second time you write the same program, it turns out better.

What's wrong with this output?

Input
```
"C is quirky,    flawed, and an    enormous success.
   While    accidents of         history
surely helped,
it    evidently satisfied a    need for a
system implementation      language   efficient enough
 to displace assembly language,
yet sufficiently abstract  and fluent to       describe
algorithms     and interactions in a
wide variety of environments." -- Dennis Ritchie
```

Output
```
"C is quirky, flawed,  and  an  enormous  success.
While  accidents  of  history  surely  helped,  it
evidently  satisfied   a   need   for   a   system
implementation  language  efficient   enough   to
displace  assembly  language,   yet   sufficiently
abstract and fluent  to  describe  algorithms  and
interactions in a wide variety  of  environments."
-- Dennis Ritchie
```


What's better with this output?

Adequate
```
"C is quirky, flawed,  and  an  enormous  success.
While  accidents  of  history  surely  helped,  it
evidently  satisfied   a   need   for   a   system
implementation  language  efficient   enough   to
displace  assembly  language,   yet   sufficiently
abstract and fluent  to  describe  algorithms  and
interactions in a wide variety  of  environments."
-- Dennis Ritchie
```

Better
```
"C is  quirky, flawed,  and  an enormous  success.
While  accidents  of  history  surely  helped,  it
evidently  satisfied   a   need   for   a   system
implementation   language  efficient   enough   to
displace  assembly  language,   yet   sufficiently
abstract and  fluent  to  describe algorithms  and
interactions in  a wide variety of  environments."
-- Dennis Ritchie
```


Challenge problem

Design a function `int spacesHere(int i, int k, int n)`

that calculates how many marbles to put into the *i*th jar, assuming that there are *n* marbles to distribute over *k* jars.

(1) the jars should add up to *n*, that is,

`{s=0; for(i=0;i<k;i++) s+=spacesHere(i,k,n); assert (s==n);}`

or in math notation, $\sum_{i=0}^{k-1}$ spacesHere(i,k,n) = n

(2) marbles should be distributed evenly—the "extra" marbles should not bunch up in nearby jars.

HINT: You should be able to write this in one or two lines, without any loops.

My solution used floating-point division and rounding; do "man round" and pay attention to where that man page says "include <math.h>".

Appendix: The "justify" Program

```c
#include <stdio.h>
#include <ctype.h>
#include <string.h>

enum {MAX_WORD_LEN = 20};
enum {MAX_LINE_LEN = 50};
```

Continued on next slide

Appendix: The "justify" Program

```c
/* Read a word from stdin.  Assign it to word.  Return the length
   of the word, or 0 if no word could be read. */

int readWord(char *word)
{  int ch, pos = 0;

   /* Skip over white space. */
   ch = getchar();
   while ((ch != EOF) && isspace(ch))
      ch = getchar();

   /* Store chars up to MAX_WORD_LEN in word. */
   while ((ch != EOF) && (! isspace(ch)))
   {  if (pos < MAX_WORD_LEN)
      {  word[pos] = (char)ch;
         pos++;
      }
      ch = getchar();
   }
   word[pos] = '\0';

   /* Return length of word. */
   return pos;
}
```

Continued on next slide

Appendix: The "justify" Program

```c
/* Append word to line, making sure that the words within line are
   separated with spaces.  lineLen is the current line length.
   Return the new line length. */

int addWord(const char *word, char *line, int lineLen)
{
   int newLineLen = lineLen;

   /* If line already contains some words, then append a space. */
   if (newLineLen > 0)
   {  strcat(line, " ");
      newLineLen++;
   }

   strcat(line, word);
   newLineLen += strlen(word);
   return newLineLen;
}
```

Continued on next slide

Appendix: The "justify" Program

```c
/* Write line to stdout, in right justified form.  lineLen
   indicates the number of characters in line.  wordCount indicates
   the number of words in line. */

void writeLine(const char *line, int lineLen, int wordCount)
{  int extraSpaces, spacesToInsert, i, j;

   /* Compute number of excess spaces for line. */
   extraSpaces = MAX_LINE_LEN - lineLen;

   for (i = 0; i < lineLen; i++)
   {  if (line[i] != ' ')
         putchar(line[i]);
      else
      {  /* Compute additional spaces to insert. */
         spacesToInsert = extraSpaces / (wordCount - 1);

         /* Print a space, plus additional spaces. */
         for (j = 1; j <= spacesToInsert + 1; j++)
            putchar(' ');

         /* Decrease extra spaces and word count. */
         extraSpaces -= spacesToInsert;
         wordCount--;
      }
   }
   putchar('\n');
}
```

Continued on next slide

Appendix: The "justify" Program

```c
/* Read words from stdin, and write the words in justified format
   to stdout. Return 0. */

int main(void)
{
   /* Simplifying assumptions:
      Each word ends with a space, tab, newline, or end-of-file.
      No word is longer than MAX_WORD_LEN characters. */

   char word[MAX_WORD_LEN + 1];
   char line[MAX_LINE_LEN + 1];
   int wordLen;
   int lineLen = 0;
   int wordCount = 0;

   line[0] = '\0'; lineLen = 0; wordCount = 0;
…
```

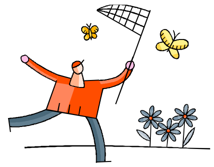
Continued on next slide

Appendix: The "justify" Program

```c
   …

   wordLen = readWord(word);
   while ((wordLen != 0)
   {
      /* If word doesn't fit on this line, then write this line. */
      if ((wordLen + 1 + lineLen) > MAX_LINE_LEN)
      {  writeLine(line, lineLen, wordCount);
         line[0] = '\0'; lineLen = 0; wordCount = 0;
      }
      lineLen = addWord(word, line, lineLen);
      wordCount++;
      wordLen = readWord(word);
   }
   if (lineLen > 0)
      puts(line);
   return 0;
}
```

Princeton University
Computer Science 217: Introduction to Programming Systems

Debugging (Part 1)



The material for this lecture is drawn, in part, from
The Practice of Programming (Kernighan & Pike) Chapter 5

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For Your Amusement

"When debugging, novices insert corrective code; experts remove defective code."

-- Richard Pattis

"If debugging is the act of removing errors from code, what's programming?"

-- Tom Gilb

"Debugging is twice as hard as writing the code in the first place. Therefore, if you write the code as cleverly as possible, you are, by definition, not smart enough to debug it."

-- Brian Kernighan

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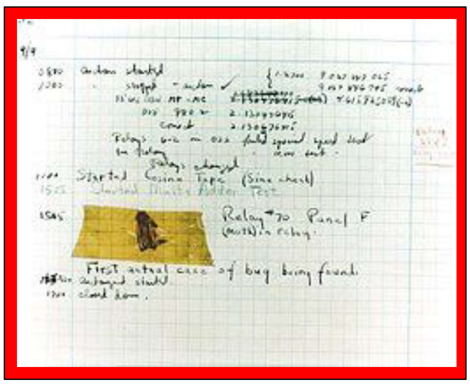
For Your Amusement



The first computer bug
(found in the Harvard Mark II computer)

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"Programming in the Large" Steps

Design & Implement
- Program & programming style (done)
- Common data structures and algorithms
- Modularity
- Building techniques & tools (done)

Test
- Testing techniques (done)

Debug
- Debugging techniques & tools <-- we are here

Maintain
- Performance improvement techniques & tools

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Goals of this Lecture

Help you learn about:
- Strategies and tools for debugging your code

Why?
- Debugging large programs can be difficult
- A power programmer knows a wide variety of debugging **strategies**
- A power programmer knows about **tools** that facilitate debugging
  - Debuggers
  - Version control systems

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Testing vs. Debugging

Testing
- What should I do to try to **break** my program?

Debugging
- What should I do to try to **fix** my program?

84

Agenda

(1) Understand error messages

(2) Think before writing

(3) Look for familiar bugs

(4) Divide and conquer

(5) Add more internal tests

(6) Display output

(7) Use a debugger

(8) Focus on recent changes

Understand Error Messages

Debugging at **build-time** is easier than debugging at **run-time**, if and only if you…

Understand the error messages!

```
#include <stdioo.h>
/* Print "hello, world" to stdout and
   return 0.
int main(void)
{  printf("hello, world\n");
   return 0;
}
```

What are the errors? (No fair looking at the next slide!)

Understand Error Messages

```
#include <stdioo.h>
/* Print "hello, world" to stdout and
   return 0.
int main(void)
{  printf("hello, world\n");
   return 0;
}
```

Which tool (preprocessor, compiler, or linker) reports the error(s)?

```
$ gcc217 hello.c -o hello
hello.c:1:20: error: stdioo.h: No such file or
directory
hello.c:2:1: error: unterminated comment
hello.c:7: warning: ISO C forbids an empty
translation unit
```


Understand Error Messages

```
#include <stdio.h>
/* Print "hello, world" to stdout and
   return 0. */
int main(void)
{  printf("hello, world\n")
   return 0;
}
```

What are the errors? (No fair looking at the next slide!)

Understand Error Messages

```
#include <stdio.h>
/* Print "hello, world" to stdout and
   return 0. */
int main(void)
{  printf("hello, world\n")
   return 0;
}
```

Which tool (preprocessor, compiler, or linker) reports the error?

```
$ gcc217 hello.c -o hello
hello.c: In function 'main':
hello.c:6: error: expected ';' before 'return'
```


Understand Error Messages

```
#include <stdio.h>
/* Print "hello, world" to stdout and
   return 0. */
int main(void)
{  prinf("hello, world\n");
   return 0;
}
```

What are the errors? (No fair looking at the next slide!)

Understand Error Messages

```
#include <stdio.h>
/* Print "hello, world" to stdout and
   return 0. */
int main(void)
{  prinf("hello, world\n")
   return 0;
}
```

Which tool (preprocessor, compiler, or linker) reports the error?

```
$ gcc217 hello.c -o hello
hello.c: In function 'main':
hello.c:5: warning: implicit declaration of function
'prinf'
/tmp/ccLSPMTR.o: In function `main':
hello.c:(.text+0x1a): undefined reference to `prinf'
collect2: ld returned 1 exit status
```


Understand Error Messages

```
#include <stdio.h>
#include <stdlib.h>
enum StateType
{  STATE_REGULAR,
   STATE_INWORD
}
int main(void)
{  printf("just hanging around\n");
   return EXIT_SUCCESS;
}
```

What are the errors? (No fair looking at the next slide!)

Understand Error Messages

```
#include <stdio.h>
#include <stdlib.h>
enum StateType
{  STATE_REGULAR,
   STATE_INWORD
}
int main(void)
{  printf("just hanging around\n");
   return EXIT_SUCCESS;
}
```

What does this error message even mean?

```
$ gcc217 hello.c -o hello
hello.c:7: error: two or more data types in declaration specifiers
hello.c:7: warning: return type of 'main' is not 'int'
```


Understand Error Messages

Caveats concerning error messages
- Line # in error message may be approximate
- Error message may seem nonsensical
- Compiler may not report the real error

Tips for eliminating error messages
- Clarity facilitates debugging
  - Make sure code is indented properly
- Look for missing semicolons
  - At ends of structure type definitions
  - At ends of function declarations
- Work incrementally
  - Start at first error message
  - Fix, rebuild, repeat

Agenda

(1) Understand error messages

(2) Think before writing

(3) Look for familiar bugs

(4) Divide and conquer

(5) Add more internal tests

(6) Display output

(7) Use a debugger

(8) Focus on recent changes

Think Before Writing

Inappropriate changes could make matters worse, so…

Think before changing your code
- Explain the code to:
  - Yourself
  - Someone else
  - A Teddy bear?
- Do experiments
  - But make sure they're disciplined

Agenda

(1) Understand error messages

(2) Think before writing

(3) Look for common bugs

(4) Divide and conquer

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Look for Common Bugs

Some of our favorites:

```
switch (i)
{  case 0:
      …
      break;
   case 1:
      …
   case 2:
      …
}
```

```
if (i = 5)
   …
```

```
if (5 < i < 10)
   …
```

```
int i;
…
scanf("%d", i);
```

```
char c;
…
c = getchar();
```

```
while (c = getchar() != EOF)
   …
```

```
if (i & j)
   …
```

What are the errors?

Look for Common Bugs

Some of our favorites:

```
for (i = 0; i < 10; i++)
{  for (j = 0; j < 10; i++)
   {  ...
   }
}
```

```
for (i = 0; i < 10; i++)
{  for (j = 10; j >= 0; j++)
   {  ...
   }
}
```

What are the errors?

Look for Common Bugs

Some of our favorites:

```
{  int i;
   …
   i = 5;
   if (something)
   {  int i;
      …
      i = 6;
      …
   }
   …
   printf("%d\n", i);
   …
}
```

What value is written if this statement is present? Absent?

Agenda

(1) Understand error messages

(2) Think before writing

(3) Look for common bugs

(4) Divide and conquer

(5) Add more internal tests

(6) Display output

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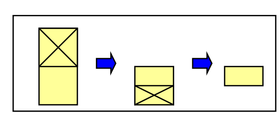
(8) Focus on recent changes

Divide and Conquer

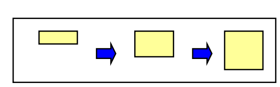
Divide and conquer: To debug a **program**…

- Incrementally find smallest **input file** that illustrates the bug

- Approach 1: **Remove** input
  - Start with file
  - Incrementally remove lines until bug disappears
  - Examine most-recently-removed lines



- Approach 2: **Add** input
  - Start with small subset of file
  - Incrementally add lines until bug appears
  - Examine most-recently-added lines



Divide and Conquer

Divide and conquer: To debug a **module**…

- Incrementally find smallest **client code subset** that illustrates the bug
- Approach 1: **Remove** code
  - Start with test client
  - Incrementally remove lines of code until bug disappears
  - Examine most-recently-removed lines
- Approach 2: **Add** code
  - Start with minimal client
  - Incrementally add lines of test client until bug appears
  - Examine most-recently-added lines

Agenda

(1) Understand error messages

(2) Think before writing

(3) Look for common bugs

(4) Divide and conquer

(5) Add more internal tests

(6) Display output

(7) Use a debugger

(8) Focus on recent changes

Add More Internal Tests

(5) Add more internal tests

- Internal tests help **find** bugs (see "Testing" lecture)
- Internal test also can help **eliminate** bugs
  - Validating parameters & checking invariants can eliminate some functions from the bug hunt

Agenda

(1) Understand error messages

(2) Think before writing

(3) Look for common bugs

(4) Divide and conquer

(5) Add more internal tests

(6) Display output

(7) Use a debugger

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Display Output

Write values of important variables at critical spots

- Poor:

```
printf("%d", keyvariable);
```

`stdout` is buffered; program may crash before output appears

- Maybe better:

```
printf("%d\n", keyvariable);
```

Printing `'\n'` flushes the `stdout` buffer, but not if `stdout` is redirected to a file

- Better:

```
printf("%d", keyvariable);
fflush(stdout);
```

Call `fflush()` to flush `stdout` buffer explicitly

Display Output

- Maybe even better:

```
fprintf(stderr, "%d", keyvariable);
```

Write debugging output to `stderr`; debugging output can be separated from normal output via redirection

Bonus: `stderr` is unbuffered

- Maybe better still:

```
FILE *fp = fopen("logfile", "w");
…
fprintf(fp, "%d", keyvariable);
fflush(fp);
```

Write to a log file

Agenda

(1) Understand error messages

(2) Think before writing

(3) Look for common bugs

(4) Divide and conquer

(5) Add more internal tests

(6) Display output

(7) Use a debugger

(8) Focus on recent changes

Use a Debugger

Use a debugger

- Alternative to displaying output

The GDB Debugger

GNU Debugger

- Part of the GNU development environment
- Integrated with Emacs editor
- Allows user to:
  - Run program
  - Set breakpoints
  - Step through code one line at a time
  - Examine values of variables during run
  - Etc.

For details see precept tutorial, precept reference sheet, Appendix 1

Agenda

(1) Understand error messages

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(8) Focus on recent changes

Focus on Recent Changes

Focus on recent changes

- Corollary: Debug now, not later

Difficult:

(1) Compose entire program
(2) Test entire program
(3) Debug entire program

Easier:

(1) Compose a little
(2) Test a little
(3) Debug a little
(4) Compose a little
(5) Test a little
(6) Debug a little
…

Focus on Recent Changes

Focus on recent change (cont.)

- Corollary: Maintain old versions

Difficult:

(1) Change code
(2) Note new bug
(3) Try to remember what changed since last version

Easier:

(1) Backup current version
(2) Change code
(3) Note new bug
(4) Compare code with last version to determine what changed

Maintaining Old Versions

To maintain old versions…

Approach 1: Manually copy project directory

```
…
$ mkdir myproject
$ cd myproject

   Create project files here.

$ cd ..
$ cp –r myproject myprojectDateTime
$ cd myproject

   Continue creating project files here.
…
```


Maintaining Old Versions

Approach 2: Use a **Revision Control System** such as subversion or git

- Allows programmer to:
  - **Check-in** source code files from **working copy** to **repository**
  - **Commit** revisions from **working copy** to **repository**
    - saves all old versions
  - **Update** source code files from **repository** to **working copy**
    - Can retrieve old versions
- Appropriate for one-developer projects
- Extremely useful, almost *necessary* for multideveloper projects!

Not required for COS 217, but good to know!

Google "subversion svn" or "git" for more information.

Summary

General debugging strategies and tools:

(1) Understand error messages
(2) Think before writing
(3) Look for common bugs
(4) Divide and conquer
(5) Add more internal tests
(6) Display output
(7) Use a debugger
- Use GDB!!!

(8) Focus on recent changes
- Consider using RCS, etc.

Appendix 1: Using GDB

An example program

File testintmath.c:

Euclid's algorithm; Don't be concerned with details

```
#include <stdio.h>

int gcd(int i, int j)
{  int temp;
   while (j != 0)
   {  temp = i % j;
      i = j;
      j = temp;
   }
   return i;
}

int lcm(int i, int j)
{  return (i / gcd(i, j)) * j;
}
…
```

```
…
int main(void)
{  int iGcd;
   int iLcm;
   iGcd = gcd(8, 12);
   iLcm = lcm(8, 12);
   printf("%d %d\n", iGcd, iLcm);
   return 0;
}
```

The program is correct

But let's pretend it has a runtime error in **gcd()**…

Appendix 1: Using GDB

General GDB strategy:

- Execute the program to the point of interest
  - Use breakpoints and stepping to do that
- Examine the values of variables at that point

Appendix 1: Using GDB

Typical steps for using GDB:

(a) Build with –g

`gcc217 -g testintmath.c –o testintmath`

- Adds extra information to executable file that GDB uses

(b) Run Emacs, with no arguments

`emacs`

(c) Run GDB on executable file from within Emacs

`<Esc key> x gdb <Enter key> testintmath <Enter key>`

(d) Set breakpoints, as desired

`break main`

- GDB sets a breakpoint at the first executable line of main()

`break gcd`

- GDB sets a breakpoint at the first executable line of gcd()

Appendix 1: Using GDB

Typical steps for using GDB (cont.):

(e) Run the program

`run`

- GDB stops at the breakpoint in main()
- Emacs opens window showing source code
- Emacs highlights line that is to be executed next

`continue`

- GDB stops at the breakpoint in gcd()
- Emacs highlights line that is to be executed next

(f) Step through the program, as desired

`step` (repeatedly)

- GDB executes the next line (repeatedly)

- Note: When next line is a call of one of your functions:
  - `step` command *steps into* the function
  - `next` command *steps over* the function, that is, executes the next line without stepping into the function

Appendix 1: Using GDB

Typical steps for using GDB (cont.):

(g) Examine variables, as desired

```
print i
print j
print temp
```

- GDB prints the value of each variable

(h) Examine the function call stack, if desired

`where`

- GBB prints the function call stack
- Useful for diagnosing crash in large program

(i) Exit gdb

`quit`

(j) Exit Emacs

`<Ctrl-x key> <Ctrl-c key>`

Appendix 1: Using GDB

GDB can do much more:

- Handle command-line arguments

  `run arg1 arg2`

- Handle redirection of stdin, stdout, stderr

  `run < somefile > someotherfile`

- Print values of expressions
- Break conditionally
- Etc.